SL 2006-058

RESEARCH ARTICLE

Sound Attenuation from Earmuffs and Earplugs in Combination: Maximum Benefits vs. Missed Information

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ABEL SM, ODELL P. *Sound attenuation from earmuffs and earplugs in combination: maximum benefits vs. missed information.* **Aviat Space Environ Med 2006; 77:899–904.**

Introduction: Noise levels from military aircraft range from 100–130 dBA. Peak pressure levels from large caliber weapons may reach 180 dB SPL. To protect against hearing loss, individuals are encouraged to wear double hearing protection. This study determined ways to maximize benefit. ***Method:*** Hearing thresholds from 0.25–8 kHz and consonant discrimination were assessed in normal-hearing subjects with ears unoccluded and fitted with highly rated earmuffs and earplugs, singly or in combination. The earplugs were available in two sizes. Selection was based on best fit. Attenuation values were derived from the threshold measurements. ***Results:*** With the muff, plug, and muff and plug in combination, thresholds ranged from 35–48 dB SPL, 40–55 dB SPL, and 44–66 dB SPL, respectively, across the frequencies tested. The combination (without regard to size of plug) resulted in attenuation values of 38–54 dB. With the smaller of the two plugs, low-frequency values as high as 53–61 dB were realized. Consonant discrimination decreased by 6–8% with the devices worn singly and by 22% with the devices in combination, relative to unoccluded listening. ***Discussion:*** Sufficient low-frequency attenuation may be achieved with muffs and plugs in combination to prevent hearing loss from operational noise. Attenuation may be maximized by choosing a smaller earplug to achieve a better fit. Possible downsides are reduced detection of warning sounds and speech intelligibility. To be heard warning sounds should surpass protected thresholds by at least 5 dB. Choosing devices which provide somewhat less attenuation may be necessary to preserve communication capability.

Keywords: hearing conservation, low-frequency noise exposure, communication deficits.

HIGH NOISE LEVELS from aircraft, small and large caliber weapons, land vehicles, ships, or submarines are characteristic of military operational environments. Continuous levels in the interior of fixed or rotary wing aircraft or in the vicinity of jet engines range from 100–130 dBA (15,18). Peak sound pressure levels from impulse noise produced by a howitzer may be as high as 180 dB SPL (28). Small caliber weapons such as assault rifles generate peak levels of about 150–165 dB SPL (15). Studies have shown that long-term exposure to unprotected 8-h A-weighted equivalent levels exceeding 85 dBA or instantaneous sound pressure levels of 140 dB will result in high-tone hearing loss (21,23). The 8-h A-weighted equivalent for a single round fired from a howitzer is 96 dB; a series of 20 rounds generates 109 dB (16). While the reduction of noise at the source through engineering controls may not be feasible in these situations, the use of personal hearing protection devices provides an easily implemented and low-cost method of hearing conservation (11).

The sound attenuation provided by hearing protection devices varies widely across makes and models, particularly for earplugs. For earmuffs, attenuation increases from about 15 dB at 0.125 Hz to about 35 dB at 1 kHz and then remains fairly stable. In general, earplugs provide relatively more attenuation (15–40 dB) below 1 kHz, but are about the same above 1 kHz for highly rated devices (11). The attenuation realized by the individual user may fall short of expectation due to problems with fitting of the device, inadequate maintenance, incorrect sizing, slack headband tension, or incompatibility with other protective gear (2,6,11). Studies of measurements made inside earmuffs with probe microphones have shown that the attenuation may be sufficient to protect against a pistol or rifle shot, but will not reduce the level of blasts from a bazooka or canon to safe levels. For these weapons protected peak levels may be as high as 170 dB SPL (28).

Individuals are encouraged to wear double hearing protectors, i.e., earmuffs and earplugs in combination, if the sound attenuation afforded by either device alone does not reduce ambient levels to the equivalent of 85 dBA over an 8-h period (26,28). As a general rule of thumb, the increase in attenuation that will accrue from the combination will be about 5 dB higher than the attenuation provided by the better of the two devices worn alone (9). Higher amounts of attenuation in the order of 40–50 dB have, however, been documented when the devices are carefully fit by the experimenter (4,12). Enhanced attenuation at the lower frequencies is a particularly important consideration in military environments owing to the prevalence of high-level low-frequency noise.

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This manuscript was received for review in April 2006. It was accepted for publication in May 2006.

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
SEP 2006		**00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE	
Sound Attenuation from Earmuffs and Earplugs in Combination: Maximum Benefits vs. Missed Information	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Defence Research and Development Canada Toronto,1133 Sheppard Avenue West,Toronto, ON, M3M 3B9 Canada,**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

A potential drawback of wearing hearing protection, single or double, is that the reduced audibility of attenuated signals may compromise the performance of auditory tasks such as the detection of warning signals and speech communication. This is particularly a concern for individuals with pre-existing hearing loss or those who are not fluent in the language spoken (1,14). In those with hearing loss, the attenuated signal may be lower in level than their raised hearing thresholds, possibly resulting in a significant hearing handicap. Nonfluency prevents subjects from taking advantage of the redundancies that normally occur in language when they fail to hear portions of the attenuated message. Evidence suggests that in normal-hearing individuals, auditory performance in noise will likely not be compromised when hearing protectors are worn. The outcome will depend on the level and frequency spectrum of the noise in combination with the attenuation characteristic of the hearing protective device worn and frequency configuration of any hearing loss (22).

The present study was conducted to determine some of the benefits and drawbacks of wearing a highly rated earmuff in combination with a highly rated earplug described by its manufacturer as having noise reduction ratings of at least 30 dB. Of particular interest was the maximum attenuation that could be realized below 1 kHz. Since speakers' voices might be reduced as well as the ambient noise, decrements in speech understanding were assessed. The devices selected were studied singly and in combination and compared with unoccluded listening in normal-hearing listeners.

METHODS

There were 2 groups of 12 men (ages 32 ± 12 yr) and 12 women (ages 30 ± 8 yr) who participated in the experiment. Subjects (military and civilian) were recruited with the aid of an e-mail sent to all employees of Defence Research and Development Canada – Toronto (DRDC Toronto) and colleagues at neighboring universities. Individuals who responded were screened by telephone for a history of ear disease, claustrophobic tendencies, or the use of medications or medical conditions that might interfere with concentration and the ability to complete the protocol. Those who met these criteria were tested for hearing loss. Only those with air conduction hearing thresholds no greater than 25 dB HL (hearing level), the clinical criterion for diagnosis of mild hearing loss, bilaterally at 0.5 kHz, 1 kHz, 2 kHz, and 4 kHz, were admitted to the study (27). The protocol was approved in advance by the DRDC Human Research Ethics Committee. Each subject provided written consent before participating.

Subjects were tested individually while seated in the center of a double-walled, semi-reverberant soundproof booth (IAC Series 1200) with inner dimensions of 3.5 m (L) × 2.7 m (W) × 2.3 m (H) that met the requirements for hearing protector testing specified in ANSI Standard S12.6–1997 (7). The ambient noise was less than the maximum permissible for audiometric test rooms specified in ANSI Standard S3.1–1999 (8).

Subjects were tested under four ear conditions: 1) unoccluded (Unoccl); and fitted with 2) Peltor H10A® earmuffs (Aearo Company, Indianapolis, IN) (Muff); 3) E-A-R earplugs, in either regular (Classic®) or small (Amigo®) size to best match ear canal size (Aearo Company) (Plug A and Plug B, respectively); and 4) the muff and plug in combination (Muff & Plug). According to the manufacturer's specifications, attenuation values for Plug A, Plug B, and the Muff for the frequencies investigated in the current study range from 36.3–47.3 dB, 35.3–47.8 dB, and 26.0–42.7 dB, respectively. Standard deviations were 5.7 dB or less.

For the protected conditions, subjects were read the manufacturers' instructions for fitting the devices before doing so themselves. The fits were then checked by the tester to ensure that the plugs were well seated in the ear canal and the muffs were well sealed to the area surrounding the outer ear. This protocol is a variation of Method A (Experimenter-Supervised Fit) described in ANSI Standard S12.6–1997 (7).

In each of the four ear conditions, measurements were made of free-field hearing thresholds for eight one-third octave noise bands centered at 0.25 kHz to 8 kHz, and consonant discrimination, in quiet. Sound attenuation was derived by subtracting the unoccluded hearing threshold from the protected threshold at each test frequency, for each of the protected ear conditions, within each subject. Consonant discrimination was assessed in each ear condition by means of the Four Alternative Auditory Feature (FAAF) test (19).

Apparatus

The one-third octave bands for the hearing threshold measurements were produced using a white noise generator (B&K 1405; Brüel and Kjaer Instruments, Norcross, GA) and band pass filter (B&K 1617; Brüel and Kjaer Instruments). Stimulus duration and envelope shape were controlled by means of a Coulbourn Instruments (Lehigh Valley, PA) modular system. The speech test was available on audiocassette and was played by a cassette deck (KX-393; Yamaha, Buena Park, CA). Outputs were fed to a manual range attenuator (HP 350-D; Hewlett-Packard, Palo Alto, CA) and receiver (RX-V620; Yamaha) and presented free-field over a set of three loudspeakers (DL10; Celestion, Maidstone, Kent, UK) positioned to create a uniform sound field. Devices were controlled from a personal computer via IEEE-488 (Institute of Electrical and Electronics Engineers, Inc., New York, NY) and LabLinc (Coulbourn Instruments) interfaces, and digital I/O lines. For the measurement of hearing thresholds, subjects used a hand-held push-button switch to indicate that they had heard the stimulus. Paper and pencil were used for the consonant discrimination task.

Procedure

Those who met the hearing screening criteria participated in one 2.5-h test session. For each ear condition, hearing thresholds were measured once for each of eight one-third octave noise bands, centered at 0.25, 0.5, 1, 2, 3.15, 4, 6.3, and 8 kHz. A variation of Békésy tracking was used (13). For each threshold determination, the stimulus was pulsed continuously at a rate of

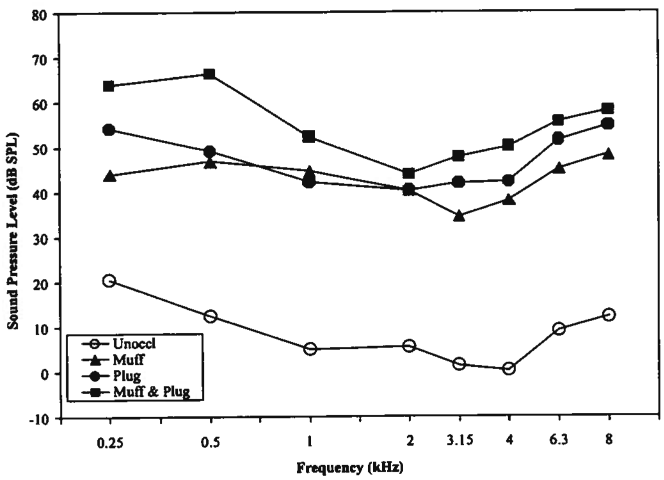

Fig. 1. Hearing thresholds (dB SPL) as a function of frequency. Effect of ear condition.

2.5 per second. The pulse duration was 250 ms including a rise/decay time of 50 ms. Subjects were instructed to depress an on/off push-button switch whenever the pulses were audible, and to release the switch when they could no longer be heard. The sound level of consecutive pulses was increased in steps of 1 dB until the switch was depressed and then decreased at the same rate of change until the switch was released. The tracking trial was terminated after a minimum of eight alternative intensity excursions with a range of 4 to 20 dB. Hearing threshold was defined as the average sound level of the eight final peaks and valleys.

For the consonant discrimination task, the subject was given a typewritten list of 80 sets of 4 monosyllabic consonant-vowel-consonant words. In half the sets, randomly distributed throughout the list, the initial consonant (e.g., wet, bet, get, yet) and in half, the final constant (e.g., bad, bag, bat, back), was contrasted. One word from each set was presented over the loudspeakers, and the subject circled the alternative heard on a typewritten form. There were five alternative lists available and these were counterbalanced across conditions and subjects in each group.

RESULTS

Fig. 1 shows the mean hearing thresholds (dB SPL) measured under the four listening conditions: Unoccl; Muff; Plug (without regard to size); and Muff & Plug, averaged across gender. In the Unoccl condition, hearing thresholds were a U-shaped function of frequency, ranging from a minimum of 0.5 dB SPL at 4 kHz to a maximum of 21 dB SPL at 0.25 kHz. For the Muff, Plug, and Muff & Plug combination, hearing thresholds ranged from 35–48 dB SPL, 40–55 dB SPL, and 44–66 dB SPL, respectively, across the eight frequencies tested. Standard deviations ranged from 4–9 dB and were similar across ear conditions and frequencies. A repeated measures analysis of variance (ANOVA, 17) applied to these data indicated that there were significant effects of ear condition, stimulus frequency, ear by frequency, and ear by frequency by gender group ($p < 0.001$).

Fig. 2 shows the sound attenuation values derived from the hearing thresholds averaged across gender. Attenuation for the Muff increased from 23 dB at 0.25 kHz to 40 dB at 1 kHz and then remained fairly stable at approximately 35 dB from 2–8 kHz. Except for a dip at 2 kHz, Plug attenuation increased monotonically from 34 dB at 0.25 kHz to 42 dB at 8 kHz. The Muff & Plug combination resulted in attenuation values in the range of 38 to 54 dB with peaks at 0.5 kHz (54 dB) and 4 kHz (50 dB). Standard deviations associated with the means plotted ranged from 3–8 dB and were similar across ear conditions and frequencies. An ANOVA applied to these data indicated that there were significant effects of ear condition, stimulus frequency, frequency by group, ear condition by frequency, and ear condition by frequency by group ($p < 0.01$ or better). Post hoc pairwise comparisons using Fisher's LSD test (17) between the means obtained for men and women revealed significant gender differences for the Plug from 0.25–1 kHz and 8 kHz, and for the Muff & Plug combination from 0.25–1 kHz ($p < 0.01$ or better). The mean attenuation achieved by women was greater by 4–9 dB than that of men.

The higher attenuation with the Plug observed for women was not expected. Previous studies had shown that women achieve less attenuation than men with plugs available in only one size (3). This finding was attributed to poor fit of a standard size plug to smaller ear canals (6). A review of the plug assignments in the present study indicated that 6 of the 12 women and 2 of the 12 men were fitted with Plug B, a smaller version of Plug A. **Table I** shows the attenuation achieved with each of Plugs A and B, alone and in combination with the Muff. An ANOVA applied to data for the Muff, Plug, and Muff & Plug for the two groups who wore Plugs A and B, respectively, showed significant effects of group, ear condition, stimulus frequency, frequency by group, ear condition by frequency, and ear condition by frequency by group ($p < 0.01$ or better). Post hoc pairwise comparisons indicated that when the plugs were worn alone, Plug B provided 10 dB more attenuation than Plug A below 2 kHz ($p < 0.001$). Differences of 3–5 dB were noted at 3.15 kHz and 4 kHz ($p < 0.05$

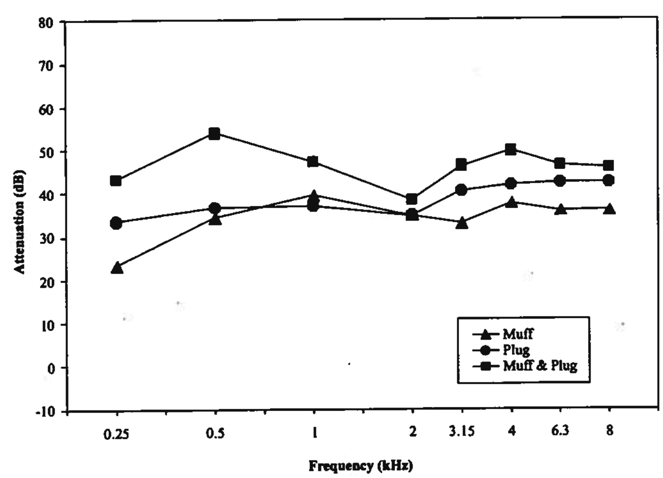

Fig. 2. Attenuation (dB) as a function of frequency. Effect of ear condition.

TABLE I. THE ATTENUATION (DB) VALUES GIVEN AS MEANS (AND SDS) OBSERVED FOR PLUG A (n = 16) AND PLUG B (n = 8), WORN ALONE OR COMBINED WITH THE MUFF.

	Ear Condition			
Freq (kHz)	Plug A	Plug B	Muff & Plug A	Muff & Plug B
0.25	30.4 (6.0)	39.5 (7.8)	38.4 (4.4)	52.6 (3.7)
0.50	33.4 (6.3)	43.0 (5.8)	50.5 (4.5)	60.6 (6.3)
1.00	33.7 (4.5)	43.7 (3.8)	44.4 (4.5)	52.6 (5.2)
2.00	34.4 (3.4)	35.7 (5.0)	37.4 (6.7)	40.4 (6.5)
3.15	38.9 (3.1)	43.4 (2.5)	44.7 (4.5)	49.0 (3.1)
4.00	40.5 (3.3)	44.2 (3.3)	48.3 (5.0)	52.3 (4.8)
6.30	42.8 (4.8)	41.5 (2.4)	46.6 (5.7)	45.8 (3.7)
8.00	42.9 (4.4)	41.5 (7.8)	45.9 (5.4)	45.6 (5.6)

or better). When the plugs were worn in combination with the muff, there were significant differences favoring Plug B with Muff of 14 dB, 10 dB, and 8 dB at 0.25 Hz, 0.5 Hz, and 1 kHz, respectively ($p < 0.001$). Significantly greater attenuation of 3–4 dB was noted from 2–4 kHz ($p < 0.05$ or better). Distributions of attenuation values observed for the two types of plug from 0.25–2 kHz in **Fig. 3** demonstrate that the higher mean values achieved with Plug B at the three lower frequencies were not due to the outcomes for one or two individuals but rather were characteristic of the group as a whole.

The results of the consonant discrimination test are displayed in **Table II**. In the Unoccl condition, both men and women obtained close to 100% correct discrimination for both initial and final consonants. Averaged across gender and consonant position, performance decreased by 6–8% when either the Muff or Plug was worn and by 22% with the Muff & Plug combination. An ANOVA applied to these data showed significant effects of ear condition, consonant position, ear

TABLE II. THE EFFECT OF EAR CONDITION ON CONSONANT DISCRIMINATION GIVEN AS MEAN PERCENT CORRECT (AND SDS) FOR 12 MALE AND 12 FEMALE SUBJECTS.

		Ear Condition			
Gender	Consonant Position	Unoccl	Muff	Plug	Muff & Plug
Male					
	Initial	97.7 (1.6)	92.1 (3.1)	88.6 (8.5)	75.2 (13.6)
	Final	96.6 (1.5)	89.4 (7.4)	89.4 (6.9)	71.4 (13.8)
	Total	97.1 (1.1)	90.7 (5.0)	89.1 (7.1)	73.1 (13.1)
Female					
	Initial	98.1 (1.4)	93.5 (3.2)	92.8 (4.8)	81.7 (11.0)
	Final	97.9 (2.0)	91.7 (4.6)	88.3 (4.3)	73.7 (9.7)
	Total	98.0 (1.5)	92.5 (3.2)	90.3 (4.1)	77.3 (10.1)
Average					
	Initial	97.9 (1.5)	92.8 (3.1)	90.7 (7.1)	78.5 (12.5)
	Final	97.3 (1.9)	90.5 (6.1)	88.8 (5.7)	72.5 (11.7)
	Total	97.6 (1.4)	91.6 (4.3)	89.7 (5.7)	75.2 (11.6)

condition by consonant, and ear condition by consonant by group ($p < 0.05$ or better). Post hoc pairwise comparisons showed that, averaged across gender groups, performance was significantly better in the Unoccl condition than with either the Muff or Plug, which were not different from each other but significantly better than the Muff & Plug combination ($p < 0.001$). Correct discrimination of the initial consonant was significantly greater than that of the final consonant (6%) only in the Muff & Plug condition ($p < 0.001$).

DISCUSSION

The goal of this investigation was to determine the amount of sound attenuation that could be achieved with a highly rated earmuff and earplug in combination, and drawbacks that might accrue for auditory

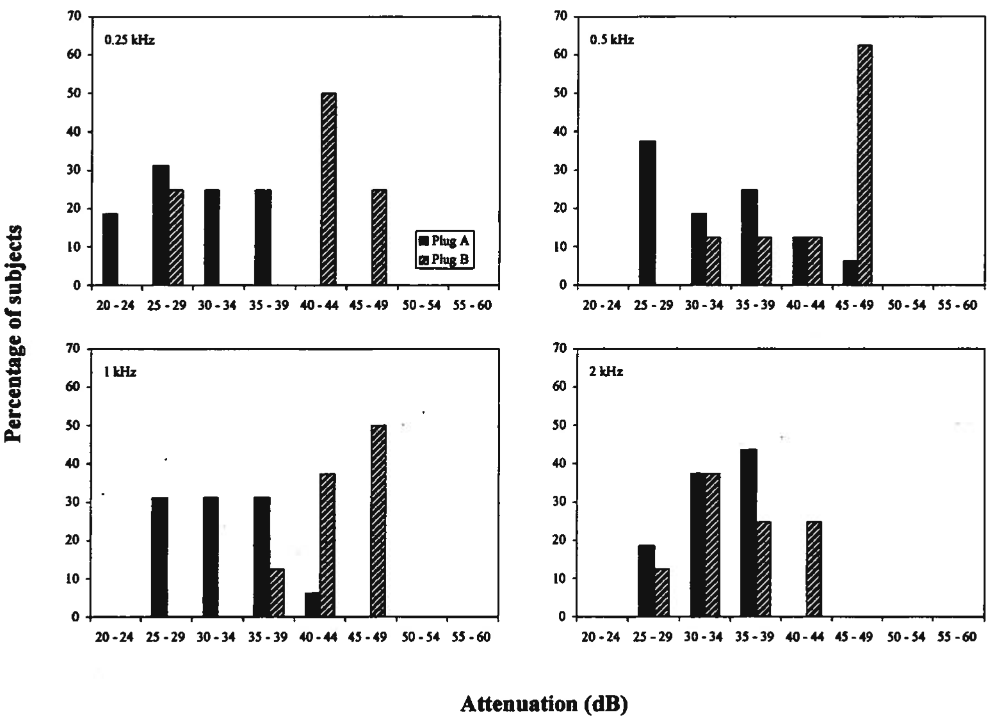

Fig. 3. Distributions of attenuation (dB) values obtained for Plug A and Plug B from 0.25 kHz to 2 kHz.

perception as a result of wearing such devices. As demonstrated previously, sound attenuation increased significantly when wearing the muff and plug in combination (4,10,12). Compared with the Muff alone (and without regard to the size of plug used), the benefit due to the combination was an additional 20 dB at 0.25 kHz and 0.5 kHz, and 10–13 dB from 3.15–8 kHz. Compared with the Plug alone the benefit was an additional 10–17 dB from 0.25–1 kHz and 3–8 dB beyond. Below 2 kHz, these observed values exceed the often quoted 5 dB rule-of-thumb prediction, which suggests that the combination will yield 5 dB more attenuation than the higher attenuation of the pair of devices worn singly (9). The observed sound attenuation, ranging from 38–54 dB across the frequencies tested (averaged across male and female subjects), would be expected to decrease both peak levels and 8-h A-weighted levels to safe exposures. They also exceed the attenuation of active noise reduction (ANR) devices which are deemed suitable for steady state noise and recommended for military aviation environments. With ANR, low-frequency attenuation typically does not exceed 25 dB (24).

Compared with the manufacturer's specifications, the mean attenuation observed for the Muff was within 3 dB from 0.25–2 kHz. At higher frequencies the observed mean attenuation fell short by 5–9 dB. Subjects who were fitted with Plug B realized a significantly greater benefit than those fitted with Plug A, alone or in combination with the Muff, on the order of 10 dB from 0.25–1 kHz. The mean attenuation for Plug A fell short of the manufacturer's specification by 10–12 dB from 0.25–1 kHz, but was within 4 dB at higher frequencies. The observations were, however, virtually identical to findings published earlier for the same device (4). The observed mean attenuation for Plug B was within 4 dB at all but 8 kHz (6 dB). The relatively poor performance of Plug A at low frequencies suggests that the likely cause was a poor seal of the device with the ear canal. These findings raise the question of whether one should, in general, err on the side of using a smaller plug. The attenuation observed for Plug B in combination with the Muff was within 5 dB of the attenuation reported by Berger et al. (12) for a deeply inserted foam plug in combination with a muff with ANR operational, and also within 5 dB of previously measured bone conduction limits (10), at all the frequencies tested in the current study.

With respect to hearing and communication, mean unoccluded values compared well with published free-field data for normal-hearing listeners (20). The Muff or Plug (without regard to size) worn alone resulted in a significant increase in threshold to values of 35–55 dB SPL (averaged across gender groups), depending on the frequency tested. By comparison, the levels with the muff and plug in combination were 46–66 dB SPL. Values in this range are indicative of a mild to moderate hearing loss (27) and lead to a concern that wearers might have difficulty detecting warning sounds. Previous studies suggest that these would have to be at least 5 dB higher, i.e., 50–70 dB SPL in the case of combined protection, to be heard 100% of the time (5). For the listener with a pre-existing hearing loss of approximately 35 dB relative to normal, the raised hearing threshold would have to be added, yielding values in the range of 85–105 dB SPL. If the hearing loss is noise-induced, then hearing at frequencies below 1 kHz are likely to be close to normal, in which case the levels required for low-frequency detection would be similar to normal (25).

The effect of reduced hearing was clearly evident for consonant discrimination. Wearing the Muff & Plug combination resulted in a 22% decrease compared with Unoccl. Wearing either device alone resulted in a decrement of only 6–8%. The impact of the decrement would depend on the operational setting and task requirements. As an example, Wagstaff and Woxen (26) recently reported on the intelligibility of common one-syllable words in helicopter noise presented at a level of 104 dB SPL. The subjects were general aviation pilots with normal hearing. They were tested with an aviation headset, alone or in combination with foam plugs, hi-fi plugs, and custom molded plugs. With the headset alone, the intelligibility score decreased from 90% when the signal level was 55 dB above the speech recognition threshold (level required for 50% correct in quiet) to 10% at 30 dB above threshold. With the foam plug in combination, the intelligibility score decreased from 35% at 55 dB above threshold to 0% at 35 dB. Lesser effects were observed for the other two plugs. The dramatic decrement in speech intelligibility with the headset in combination with the foam plug was attributed to the high combined attenuation at the mid to high speech frequencies and the masking effect of the low-frequency noise.

Conclusions

The results of this study lead to the conclusion that highly rated earmuffs and earplugs in combination will provide sufficient protection against steady state and impact noise from military aircraft and weapons. The attenuation that may be realized by the individual user may be maximized by choosing an earplug in a smaller size to achieve a better fit. The downsides of improved protection are reduced detection of warning sounds and speech intelligibility. Detection should not be a concern as long as the levels of these sounds surpass protected thresholds by at least 5 dB. This may be difficult to achieve in cases of hearing loss, particularly at high frequencies. With respect to speech intelligibility, the present and related previous studies suggest that to maintain performance it will be necessary to increase the speech-to-noise ratio with increases in both the level of the background and attenuation of the hearing protector worn. Users may decide to choose devices which provide somewhat less attenuation in order to preserve communication capability.

ACKNOWLEDGMENTS

This research was funded by the Military Operational Medicine Thrust, Defence R&D Canada. The authors extend their thanks to the men and women who graciously gave their time to participate as subjects. They are also grateful to the reviewers of an earlier draft of the manuscript for their suggested revisions.

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